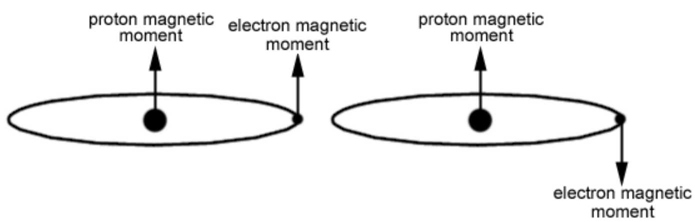
RADIO ASTRONOMY

Radio astronomy began in 1932, when Karl G. Jansky discovered the existence of radio waves of extraterrestrial origin. It is now a well-established and important branch of observational astronomy. Radio astronomy is a study of celestial objects at radio frequency. The radio frequency range is 30 MHz to 40 MHz (wavelength range 10 m to 7 mm).

Basic Principle:

Hydrogen atom consists of a proton and an electron. The spins of the two particles can be aligned or anti aligned. If they are aligned, the atom has slightly more energy than if the spins are anti aligned.

A H-atom can make a transition from the aligned state to anti aligned state and emits radio energy of wavelength 21cm (frequency 1420 MHz). Conversely if the atom is exposed to 21 cm wavelength energy, it makes a transition from anti aligned state to aligned state. This 21 cm line is fundamental to radio astronomy.



By studying the 21 cm line, we learn the following:

- velocity of neutral hydrogen clouds (from doppler shifts)
- rotation of our galaxy and other galaxies (from doppler shifts)
- distribution of neutral hydrogen in our galaxy and in other galaxies (from images)
- tidal interactions between galaxies (from images and doppler shifts)
- amount of gas in the interstellar medium (from strength of the lines)

Sources of Radio Waves

Pulsars, Quasars, Radio galaxy, Microwave back ground radiation etc are the sources of radio waves. These astronomical objects emit radio waves by one of several processes, including (1) thermal radiation from solid bodies such as the planets, (2) thermal, or bremsstrahlung, radiation from hot gas in the interstellar medium, (3) synchrotron radiation from electrons moving at velocities near the speed of light in weak magnetic fields, (4) spectral line radiation from atomic or molecular transitions that occur in the interstellar medium or in the gaseous envelopes around stars, and (5) pulsed radiation resulting from the rapid rotation of neutron stars surrounded by an intense magnetic field and energetic electrons.

RADIO TELESCOPES

Radio telescope, an astronomical instrument used to detect radio-frequency radiation between wavelengths of about 10 metres (30 megahertz [MHz]) and 1 mm (300 gigahertz [GHz]) emitted by extraterrestrial sources, such as stars, galaxies, and quasars.

Naturally occurring radio waves are extremely weak when they reach us from space. A cell phone signal is a billion and billion times more powerful than the cosmic waves our telescopes detect. So radio telescopes are usually very large—up to hundreds of metres across—and use the most sensitive radio receivers available.

Parts of a Radio Telescope

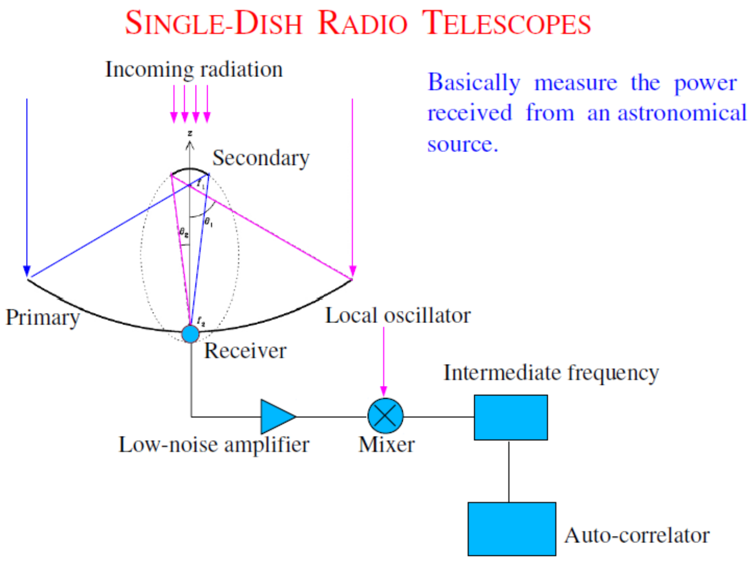
Radio telescopes have two basic components: (1) a large radio antenna and (2) a sensitive radiometer, or radio receiver. The sensitivity of a radio telescope—i.e., the ability to measure weak sources of radio emission—depends both on the area and efficiency of the antenna and on the sensitivity of the radio receiver used to amplify and to detect the signals. For broadband continuum emission over a range of wavelengths, the sensitivity also depends on the bandwidth of the receiver.

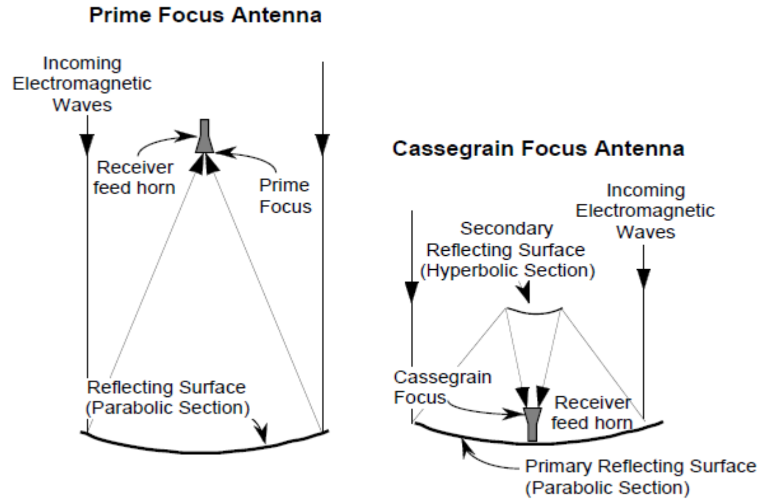
The Antenna and Receiver

The most versatile and powerful type of radio telescope is the parabolic dish antenna. The parabola is a useful mathematical shape that forces incoming radio waves to bounce up to a single point above it, called a focus.

Dish antennae bounce many different wavelengths at once, and we need different receivers to tune to different frequency channels for the different kinds of research we do. To observe a specific wavelength range, we select a specific size funnel to grab the radio waves we want. These funnels are called feed horns.

In the simplest form of radio telescope, the receiver is placed directly at the focal point of the parabolic reflector, and the detected signal is carried by cable along the feed support structure to a point near the ground where it can be recorded and analyzed. More often, a secondary reflector is placed in front of (Cassegrain focus) or behind (Gregorian focus) the focal point of the paraboloid to focus the radiation to a point near the vertex, or centre, of the main reflector.





The **angular resolution**, or ability of a radio telescope to distinguish fine detail in the sky, depends on the wavelength of observations divided by the size of the instrument.

Angular resolution = $\frac{\lambda}{d}$

λ source wavelength

d size of the instrument.

If d is large, the angular resolution is minimum. To built large telescope it needs more cost. To overcome the difficulty array of antenna is used in RA. In a simple two antenna radio interferometers, the signal from a point source arrive in phase/ out of phase (constructive/ destructive) as earth rotates and causes a change in the path difference produce fringes.

Data Processing

Modern radio telescopes observe a large number of frequencies all at once, with computers dividing the frequency band into as many as several thousand separate channels that may range over tens to hundreds of megahertz.

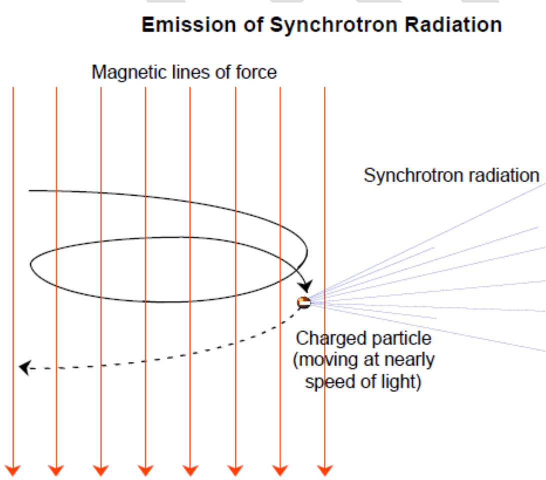
SYNCHROTRON RADIATION

When a charged particle enters a magnetic field, the field compels it to move in a circular or spiral path around the magnetic lines of force. The particle is thus accelerated and radiates energy. There are two types of radiation depends on velocity of particles.

i) **Cyclotron Radiation:** If the velocity of the particle is non relativistic velocity ie $v << c$ then the radiation is cyclotron radiation.

ii) **Synchrotron Radiation:** If the velocity of the particle is relativistic velocity ie $v \approx c$ then the radiation is Synchrotron radiation.

The cyclotron radiation is not strong enough to have much astronomical importance. But synchrotron radiation has astronomical importance. Quasars are one source of synchrotron radiation not only at radio wavelengths, but also at visible and x-ray wavelengths.



Equation of motion of particle in a magnetic field

$$\frac{d}{dt}(mv) = \frac{q}{c}(v \times B)$$

If we include g – Lorentz factor in the above equation

$$g\frac{d}{dt}(mv) = \frac{q}{c}(v \times B)$$

Since the force on the partice is perpendicular to the motion, its speed does not change ie $|v| = constant$. The particle has constant speed v, but its direction can change.

$$\frac{dv_{\parallel}}{dt} = 0$$

$$\frac{dv_{\perp}}{dt} = \frac{q}{gmc}\,(v_{\perp} \times B)$$

It is uniform circular motion around the field lines of the magnetic field B.

If the velocity along the field lines is non zero, then the particle moves in a helical path along the field.

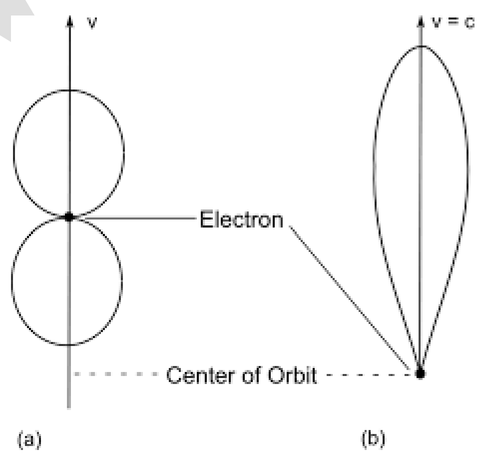
$$\frac{v^2}{r} = \frac{q}{gmc}\; vB\, sin\theta$$

This is centrifugal acceleration. r – radius of gyration; θ - pitch angle.

Power emitted in the synchrotron process $P = \frac{2\,q^2}{3c^3}\, g^4\theta^2$

In non relativistic case, the power emitted by a accelerated particle has a characteristic two lobe distribution around the direction of acceleration. In relativistic case, it is a single lobe.

As the electron cycle around the helical path along the magnetic field line, any emission directed towards a distant observer can be seen only when the beam is aligned with the observer's line of sight.



SPECTRAL-LINES IN RA

Spectral-line radiation from interstellar gas clouds is generated by atoms and molecules whenever they lose or gain energy in collisions with each other, or are excited by nearby stars. The relative intensities, frequencies and widths of the lines are set by physical conditions, and depend on the molecular species, its density, and temperature and velocity distribution.

Types of spectral lines

Several types of spectral lines are observed by radio astronomers. The most important of these spectral lines is the 21-centimetre line emitted by neutral hydrogen atoms. The Dutch astronomer Hendrik C. van de Hulst predicted this line in 1944, and it was first detected in 1951. This detection was an important milestone in astronomy, as it provided the very first overall picture of the true spiral structure of our own Galaxy.

We now know that neutral atomic hydrogen is abundant in most galaxies, which gives this spectral line fundamental importance for enabling the study of interstellar gas in galaxies in general. Studies of spectral lines in our Galaxy provide information about molecular clouds, the processes of stellar evolution, and about the Galaxy's spiral structure and chemical evolution. These properties are also being investigated now in other galaxies, with the improved sensitivity and angular resolution of the newer arrays.

Molecular lines arise in several types of interstellar gas clouds: diffuse low-density clouds; isolated, cool dark clouds often containing molecules that are unstable on Earth; and giant, dense molecular clouds containing HII regions, hot young stars, and stars in process of formation. The 18-centimetre line of the hydroxyl (OH) radical was detected in 1963, and the lines from water (H_2O), ammonia (NH_3), formaldehyde (H_2CO), and carbon monoxide (CO) were identified in 1968–70. The total number of molecules and radicals so far detected stands at more than 200. Radio spectral lines from such molecules are associated with cold, dense interstellar clouds thought to be sites of star formation. A number of these clouds have been discovered near the centre of the Milky Way Galaxy

Maser lines are a special type of spectral line that is only supported by a few molecules. They are created by amplification of background continuum radiation, and in our Galaxy are intense, very narrowband, and often polarized. They are of particular interest because they can pinpoint dense regions within clouds where stars are being formed, while some may also be associated with the extended envelopes of evolved stars.

Recombination lines are emitted by atoms of hydrogen, helium, carbon, etc., when their electrons move from a higher to a lower energy state. Observation of the strength and shape of recombination lines enables us to determine the physical conditions giving rise to them.

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MAJOR DISCOVERIES IN RA

Radio astronomy has an essential role in the investigation of the fundamental physics and astronomy of the Universe. The astronomical objects emit radio waves by one of several processes, including thermal radiation, bremsstrahlung, synchrotron radiation, spectral line radiation and pulsed radiation. By studying these radio signals with the help of radio telescopes numerous numbers of discoveries have been made. Using radio telescopes equipped with sensitive spectrometers, radio astronomers have discovered about 150 separate molecules, including familiar chemical compounds such as water, formaldehyde, ammonia, methanol, ethyl alcohol, and carbon dioxide. Here we will discuss few major discoveries in RA

1) UNDERSTANDING OF OUR UNIVERSE: COSMIC MICROWAVE BACKGROUND

Cosmic Microwave Background (CMB) radiation had been discovered in the year 1964. The CMB has a 2.73 K brightness temperature. This radiation, which comes from all parts of the sky, is thought to be the remaining radiation from the hot big bang, the primeval explosion from which the universe presumably originated 13.7 billion years ago. With this discovery the RA made the Big Bang theory became the accepted macroscopic description of the history of our Universe and eliminated the Steady State theory from contention.

2) MAPPING OF OUR GALAXY:

Some components of the Universe can only be studied by means of their radio frequency signatures. This is particularly the case for its most abundant material component, neutral hydrogen (HI), which is only detected via its 1420 MHz spectral line. Once the distribution of HI was mapped in our own Milky Way Galaxy, the centre of the Galaxy was finally located, its spiral arms were mapped, and our sun's remote location established to be in an outer spiral arm. Mapping the continuum radiation of our Galaxy, we know the exact position of its centre, and a very strong radio source, a super massive black hole.

3) SOLAR SYSTEM:

Radio telescopes are used to measure the surface temperatures of all the planets, as well as some of the moons of Jupiter and Saturn. Radar measurements have revealed the rotation of Mercury, which was previously thought to keep the same side toward the Sun. Astronomers have also used radar observations to image features on the surface of Venus, which is completely obscured from visual scrutiny by the heavy clouds.

4) DISCOVERY OF PULSARS:

The discovery of pulsars - *pulsating radio stars* in 1967 revealed the existence of rapidly rotating neutron stars throughout the Milky Way Galaxy and led to the first observation of the effect of gravitational radiation. Pulsars are associated with Neutron Stars. The collapsed neutron star starts spinning at a fraction of second. Its magnetic field becomes tens or hundreds of billions Gauss, resulting in beamed radiation in the direction of their magnetic poles. About 1700 pulsars have been now catalogued so far.

5) DISCOVERY OF RADIO GALAXIES, QUASARS AND ACTIVE GALAXIES

Quasar, an astronomical object of very high luminosity found in the centres of some galaxies and powered by gas spiraling at high velocity into an extremely large black hole. The brightest quasars can outshine all of the stars in the galaxies in which they reside, which makes them visible even at distances of billions of light-years. Quasars are among the most distant and luminous objects known.

Active galactic nucleus (AGN), small region at the centre of a galaxy that emits a prodigious amount of energy in the form of radio, optical, X-ray, or gamma radiation or high-speed particle jets.

Radio galaxies and quasars are the most energetic celestial objects in the universe. It is now well established that these highly energetic objects are associated with active galactic nuclei (AGNs) that are powered by massive black holes with masses of tens to hundreds of millions solar masses.

Radio telescopes have discovered powerful radio galaxies and quasars far beyond the Milky Way Galaxy system. AGNs give rise to jets of relativistic particles that interact with the intergalactic gas and emit radio waves by synchrotron process. Observations at metre wavelengths have provided valuable vital information about these objects such as their age, cosmological evolution, etc.

6) ORIGIN AND EVOLUTION OF THE COSMIC MAGNETISM

Radio Astronomy determines evolution of magnetic field from early times to now, through studies of Faraday rotation, polarization of synchrotron radiation and Zeeman effect.

7) DARK MATTER: BLACK HOLES IN THE UNIVERSE

The presence of massive black holes at the centre of active galaxies was firstly established by radio astronomy observations, is now firmly established from Radio, Optical and X-ray observations.

It has been established from measurements that the rotational velocities of the hydrogen clouds vary with distance from the galactic centre. The mass of a spiral galaxy can in turn be estimated using this velocity data. In this way radio telescopes show evidence for the presence of so-called dark matter by showing that the amount of starlight is insufficient to account for the large mass inferred from the rapid rotation curves.

It is now clear that almost all galaxies have massive black holes of millions of solar mass including our Galaxy. Stellar size black holes have also been discovered in our Galaxy. OJ287 is considered to have an object of 100 million Suns in a binary orbit around a Black Hole of 17 Billion Suns**.**

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RADIO ASTRONOMY IN INDIA

During the last 40 years several radio telescopes have been built in India, being amongst the best in the world. These have yielded many important results concerning a variety of radio sources in the universe. The Indian radio astronomy groups have also contributed significantly to the construction of radio telescopes in Brazil and Mauritius.

Important scientific contributions and discoveries have been made by Indian radio astronomers in a wide variety of topics such as radio emission from the sun, pulsars, HII regions, recombination lines, supernova remnants, and centre of our galaxy, dwarf galaxies, nearby galaxies, supernovae, radio galaxies, quasars, HI studies and cosmology.

The relatively lower radio noise environment in India compared to that in the western countries, has allowed construction of several large facilities for operation at metre wavelengths. Let we see few radio telescopes installed in India and some radio astronomy research centers.

The Kalyan Radio Telescope

Tata Institute of Fundamental Research **(TIFR),** set up a grating-type radio interferometer at Kalyan near Bombay in 1965 for observing the sun at a frequency of

610 MHz under the headship of Prof Govind Swarub. The interferometer consisted of 32 parabolic dishes of 1.8 m diameter. The telescope was used for studying the quiet and active regions of the sun during. It was found that the quiet sun had considerable limb-brightening at 610 MHz and that the solar corona had a temperature of 10^6 K. Solar radio bursts were also observed at 610 MHz. The radio astronomy group of Tata Institute of Fundamental Research **(**TIFR) has made many valuable contributions concerning cosmology, extra-galactic radio sources, galactic radio sources and interplanetary medium.

The Ooty Radio Telescope

ORT was the first major facility in India which firmly established the country on the world map of radio astronomy. The ORT consists of a 530 m long and 30 m wide parabolic cylinder. Its design makes full use of India's proximity to the geographical equator. The main feature of the telescope is parallel to earth axis so no need to rotate the telescope to compensate for earth rotation. ORT rotates about single axis. ORT operates at a frequency of 325 MHz. The RF bandwidth of the ORT is about 16 MHz.

ORT has made important contributions concerning cosmological evolution of radio galaxies which favours Cold Dark Matter model, Galactic center, fine structures of radio sources, pulsars, solar wind and so on. Observations with the ORT during 1970s led to discovery of **eight new pulsars**.

The Giant Metrewave Radio Telescope (GMRT)

GMRT was installed at Khodad near Pune in 1980. There are 30 dishes 45 m in diameter span in 25 Km area. Operating frequency is 150 MHz to 1420 MHz. It studies Microwave Background radiation and pulsars. A noteworthy feature of the GMRT is its hybrid design. GMRT is now being upgraded to provide more or less continuous frequency coverage from 40 MHz to 1430 MHz and a bandwidth of 256 MHz or even 400 MHz. GMRT is the most powerful radio telescope operating at metre wavelengths in the world. GMRT is being used by astronomers from 22 countries. Its unique frequency coverage allowed one to detect sources that were not observable at other observatories.

A few notable pulsars have been discovered using the GMRT. In particular, a large scale of work on radio galaxies, quasars, cluster of galaxies, nearby galaxies, transients, interstellar medium (ISM) of our galaxy, supernova remnants, HII regions and sun has been done by GMRT.

Radio Astronomy at the Indian Institute of Astrophysics, Bengaluru

The main focus of the radio astronomy facilities at the IIA concerns observations of sun at low frequencies, viz. 30-150 MHz. It conducts study on galaxies, supernovae, radio galaxies, quasars, pulsars, active galactic nuclei etc.

Radio Astronomy at the Raman Research Institute, Bengaluru

Studies on interstellar Deuterium to hydrogen ratio, the spectral line activity and Radio Recombination Lines (RRL) have been carried out. Radio recombination lines can be excellent probes of density and temperature of the ionized regions. Study of the kinematics of interstellar gas and of galaxies in clusters and groups using the 21 cm hyperfine transition of neutral hydrogen has been a sustained theme at RRI.

Radio Astronomy at the Physical Research Laboratory, Ahmedabad

Studies on Interplanetary Scintillations, Solar Wind and Solar Studies have been conducted here.

Hot Big Bang Cosmology: Early Universe

If we run the clock backward, we deduce that in the past the universe was smaller, denser, and hotter than it is today. We can use gas physics and particle physics to understand the early, hot phase of the universe

Cosmic Microwave Background Radiation

When the universe was young, it was hot enough for gas to be ionized. As the universe expanded and cooled, the electrons and ions were able to come together to form neutral atoms. Suddenly the photons were liberated, free to travel great distances through the universe. Those photons are still around and visible as the cosmic microwave background (CMB) radiation.

Hot Big Bang

We said the universe was hotter when it was younger, but to study the CMB we need to quantify that statement. For our purposes here first we characterize the expansion using the dimensionless scale factor a(t) such that distances scale as a and volumes scale as a^3 relative to today. Second, the expansion causes light waves to stretch, creating the **cosmological red shift**.

the ratio of observed and emitted wavelengths is

$$\frac{\lambda_{obs}}{\lambda_{em}} = \frac{1}{a}$$

Suppose the universe today is filled with blackbody radiation with some temperature T_0. In the past, the wavelengths were all smaller by the factor a. From the Planck spectrum or Wien's law wavelength and temperature are related by λT = constant which immediately implies

$$T \propto a^{-1} \text{ or } T = \frac{T_0}{a}$$

This allows us to characterize how the universe has cooled as it has expanded. We also need to specify how the density has changed.

conservation of mass implies

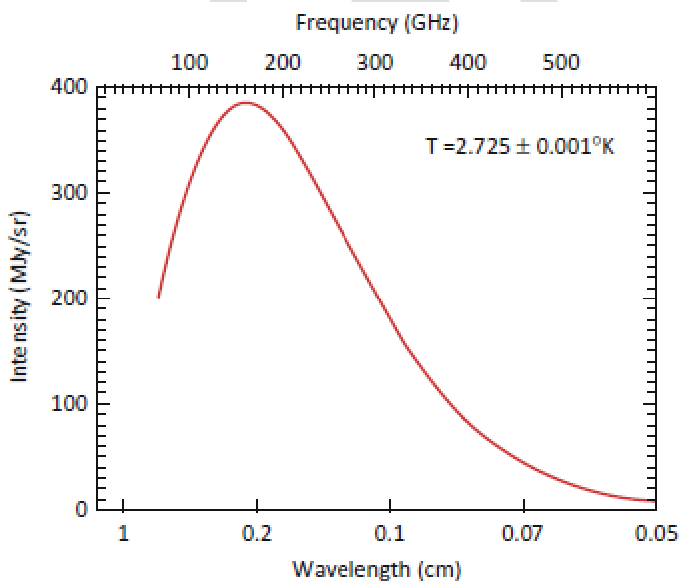
$$\rho \propto a^{-3} \quad \text{or } \rho = \frac{\rho_0}{a^3}$$

we can write a relation between density and temperature: $\frac{\rho}{\rho_0} = \frac{T^3}{{T_0}^3}$

As the universe expanded, the photons had to **decouple** from matter. As the universe cooled, electrons and ions were able to combine to form neutral atoms in a process known as **recombination**. The gas effectively became transparent.

We can estimate the temperature of the universe at recombination, which helps us understand the state of the universe that we study when we observe the CMB. For simplicity, let's assume the universe was pure hydrogen.

The analyses indicate that the temperature had to be a little lower, around 3000 K, for recombination to be complete. Mapping the CMB is a vital part of cosmology today. The first detailed maps were obtained by the Cosmic Background Explorer (COBE, launched in 1989). The CMB spectrum measured by COBE matches a theoretical blackbody spectrum well. This is the first piece of evidence that we truly understand what was happening in the early universe.



The curve shows a theoretical blackbody spectrum with a temperature of 2.725 K. Points

Big Bang Nucleosynthesis

The CMB provides direct access to the physical state of the universe when it was about 380,000 years old. We can reach back even further—to when the universe was only a few minutes old—by using the idea that the very young universe was a nuclear reactor.

The timeline

13.6 billion years ago T=0, the Universe began with the big bang

- **T = 1/1,000,000 seconds - temperature is 10 trillion Kelvin - light elements form: photons, quarks, neutrinos, electrons (no protons or neutrons)**
- T = 1/100 seconds - temperature is 100 billion Kelvin - protons and neutrons form
- T = 1/10 seconds - temperature is 50 billion Kelvin - Neutrons less stable and convert back to photons - 60% protons, 40% neutrons - protons join to form deuterium, but unstable at high temperature - deuterium bottleneck
- **T = 1 second - temperature is 10 billion Kelvin - deuterium bottleneck still, now 75% protons and 25% neutrons**
- T = 14 seconds - temperature is 4 billion Kelvin - deuterium bottleneck still, now 82% protons and 18% neutrons
- **T = 3 minutes - temperature now under 1 billion Kelvin - deuterium can form (2 protons form nucleus), helium (4 protons) also forms**

The first 3 minutes of the Big Bang resulted in the nucleosynthesis of both hydrogen and helium - without electrons. Also during this time the temperature rapidly decreased while the expansion rapidly increased.

Now for a more "slow" evolution:

- T = 35 minutes - temperature is now 300 million Kelvin - temperature still to hot for hydrogen and helium to bind electrons, increased neutrinos and antineutrinos by positron annihilation

- **T = 1000 years - temperature is now 100,000 Kelvin - bridge between radiation dominated and matter dominated Universe - Dark Energy**
- **T = 300,000 years - temperature is now only a few thousand Kelvin - recombination transition - electrons can now bind with deuterium and helium nucleus' - Universe becomes transparent - CMB**

Prior to T = 1000 years, radiation in the form of photons and neutrinos dominated the Universe. Deuterium and helium nuclei were still forming but electrons could not be bound. Prior to T = 300,000 years, the Universe was opaque mainly because of the dominate free electrons. Once the recombination transition was reached, the Universe became transparent.

- T = 300,000 years after the big bang, protons and neutrons form (combined from residual quarks)
- T = 300,000 to 10,000,000 years - recombination, that is hydrogen atoms form (this is what we see in the Cosmic Background Radiation)
- T = 10,000,000 to 1,000,000,000 years - clumps of matter combine to form proto-galaxies
- T = 1,000,000,000 to 3,000,000,000 years quasars form
- **T = 3,000,000,000 to 8,000,000,000 years, galaxies form**
- **T = 8,000,000,000 to 12,000,000,000 years, our Solar System and planets**
- **The Universe is expanding, with the most distant galaxies (quasars) expanding faster than nearby galaxies**

We can explain how the elements were created in the universe as follows: Combining that with our understanding of gas (for the CMB) and stars, we can get the contents of the universe as : today the universe contains about 5% normal matter, 27% dark matter, and 68% dark energy.

From the standard model **"Lambda-Cold Dark Matter**" model of cosmology: the universe comprise "Dark Energy" 70% of critical density, "Dark Matter" 25% of critical density. Ordinary baryonic matter 5% of critical density , the form of matter that is most directly measurable is the familiar protons, neutrons and the like that make up the ordinary matter of starts and planets and Radiation 0.005% of critical density.

Note: in the above time line you may **take the bold line points** and skip the remaining